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Fatigue properties of high-strength steel in diesel oil

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Abstract

This paper describes the fatigue properties of chromium-molybdenum steel in air and diesel oil. 4-point bending fatigue tests were conducted at a stress ratio of R=0.05. The corrosion mark was not confirmed on the specimens tested in diesel oil, and the fatigue strength at $N_f < 3\times10^4$ improved and that at $N_f > 3\times10^4$ declined compared to in air. The fatigue crack initiation life accounted for about 90 % of the fatigue life N_f. The results of the elemental analysis of the specimen surface tested in diesel oil which were broken at $N_f > 3\times10^4$, O, Si, and C had been concentrated. The reduction of fatigue strength at $N_f > 3\times10^4$ is considered to be caused by some influence of deterioration of the diesel oil winhich progress with the fatigue test. On the other hand, the fatigue test at $N_f < 3\times10^4$ is usually finished within one day, so diesel oil does not have the time to deteriorate. Then, a few fatigue tests were conducted in the deteriorated diesel oil at a relatively high stress range, in order to break the specimen at $N_f < 3\times10^4$. As a result, fatigue life tends to shorten. Therefore, it was found that the diesel oil deterioration should be considered as one of the important factors to explain the decrease of fatigue strength.

Keywords: Fatigue strength, Effect of fuel, Diesel oil, High-strength steel

1. Introduction

The use of automobiles expands with the developments in car technology in all over the world. In addition, the number of diesel car in Europe is increasing year by year. The diesel car has been advanced high pressure of fuel for the purpose of exhaust gas reduction and thermal efficiency improvement. So stress applied to the product tends to

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increase. In addition, the shift from fossil fuel to environment friendly source of energy, related to the usage of biofuel (fatty acid methyl ester) made from a vegetable oil as a raw material, has been widely expanded lately. Also, the use of fuel mixed with water or acid has been confirmed in emerging countries, and fuel is progressing diversification and adulteration. In such fuel environment, the fatigue strength decrease of the product by the materials deterioration caused by the fuel is confirmed. Indeed, a previous study reported that the fatigue properties of stainless steel decrease in biofuel with 85 % ethanol in gasoline (Schmid, *et al*. 2014). In addition, the effects of diesel oil and biofuel on the fatigue properties of Al alloy has been studied in rotating bending fatigue test with oil-dropping method (Kawagoishi, *et al*. 2012). However, despite such experimental works, the mechanism of the strength reduction of metallic materials in fuel environment is not clear. Besides, another research on the impact of oil and corrosion products into the fatigue crack propagation has been undertaken in rotating bending fatigue test in corrosive liquid or with oil-dropping method (Misawa 1976, Kawagoishi, *et al*. 1988). Even though such a work does not involve fuel influence, the experimental approach is similar.

As mentioned above, up to now studies performed in diesel oil environment in order to investigate the effect of diesel oil on fatigue properties of metallic materials are not sufficient to get an overview of the fatigue strength reduction mechanism. Thus, further researches on the material strength and fracture behaviour in diesel oil are needed. In this study, a new fatigue strength evaluation technique in fuel environment was developed in order to investigate concretely the fatigue properties and strength reduction phenomenon in diesel oil.

Nomenclature

σ_{max}	maximum bending stress	σ_{min}	minimum bending stress
σ_w	fatigue limit	σ_r	residual stress
$\Delta\sigma$	stress range	P_{max}	maximum load
L	lower part span (= 30 mm)	R	stress ratio
l	upper part span (= 10 mm)	N_f	number of cycles to failure
b	specimen width	N	number of cycles
d	specimen height	TAN	total acid number
T	temperature	HV	Vickers hardness

2. Experimental work

2.1. Material and specimens

The material examined in this work was a chromium-molybdenum steel (JIS SCM415). The chemical composition of the material is shown in Table 1. All specimens were taken from bars of ϕ45 parallel to rolling direction and machined into dimensions shown in Fig. 1. Then the specimens were heat treated by vacuum carburizing. After the heat treatment, a martensitic microstructure was observed near the specimen surface by optical micrograph (OM). The Vickers hardness and the longitudinal residual stress distribution measured along the depth direction are shown in Fig. 2. The hardness of the surface is 708 *HV*, and surface residual stress is -173 MPa. In addition, the residual stress was measured by using X-ray diffraction method.

Table 1. Chemical compositions of JIS SCM415 (mass %).

C	Si	Mn	P	S	Ni	Cr	Mo	Ti	Al	Bi	Fe
0.13-0.18	0.15-0.35	0.60-0.90	≦ 0.030	≦ 0.031	≦ 0.25	0.90-1.20	0.15-0.25	0.007	*	*	bal

* Very small amount

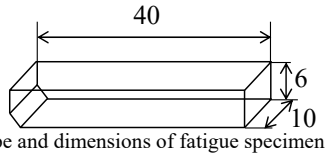

Fig. 1 Shape and dimensions of fatigue specimen (unit in mm).

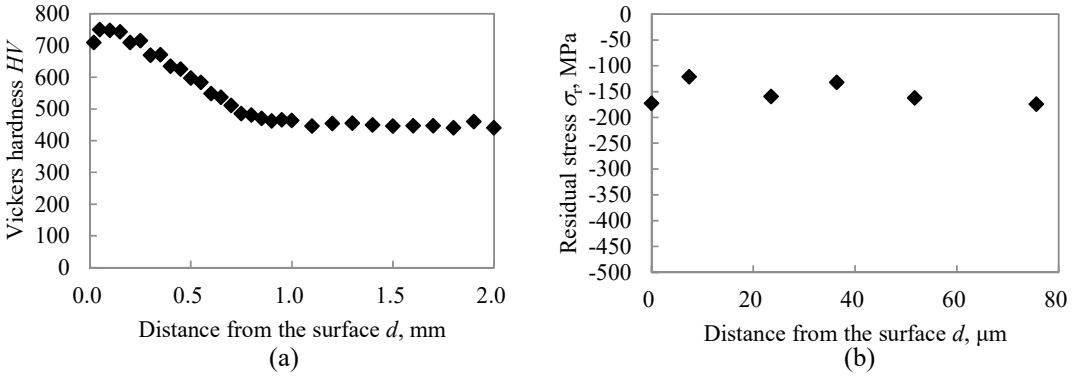

Fig. 2 Mechanical properties: (a) Vickers hardness and (b) longitudinal residual stress distribution measured along the depth direction.

2.2. Equipment and Testing Method

The loading condition of fatigue tests accepted in this study is 4-point bending configuration. Fatigue tests were performed using electro-hydraulic fatigue testing machine operating at 20 Hz. The stress ratio of all tests was R = 0.05. Maximum bending stress σ_{max} which is applied on specimen surface was calculated as following Eq. (1).

$$\sigma_{max} = \frac{3P_{max}(L-l)}{2bd^2} \tag{1}$$

where P_{max} is maximum load, L is lower part span, l is upper part span, b is specimen width, and d is specimen height, respectively. The fatigue tests were carried out up to 10^7 cycles in a sinusoidal waveform. In this research, the fatigue test was performed by the *14S-N method* and fatigue limit was determined by a *staircase method*.

A schematic illustration of the newly developed fuel circulation system is shown in Fig. 3(a). To carry out fatigue tests in fuel, test environment is necessary to seal space to prevent leakage and volatilization of the fuel. Therefore, 4-point bending jig was surrounded by an acrylic pipe, which is sealed by a mechanical part on the upper side, as shown in Fig. 3(b). The fuel was pumped and circulated in the test chamber at about 60 ml/min by an explosion-proof pump. With respect to the circulation of the fuel, the long-time use of the same fuel may cause excessive deterioration. Therefore, it is necessary to stabilize properties of the fuel inserted in the test chamber during the fatigue test. In this research, the fuel temperature inside the test chamber should be controlled in 80 ± 10 °C range in order to approach the in actual service conditions. In addition, the fuel was changed so that the fuel deterioration degree (total acid number) became less than 0.25 mgKOH/g. Fig. 4(a) shows the relationship between time and temperature of the test chamber when fuel tank heater temperature is 120 °C and laying pipe heater temperature is 85 °C, resulting that the fuel temperature in the test chamber is controlled in accordance with the range already discussed. In addition, the total acid number of the fuel analysis was measured by potentiometric method, also the water content was measured by the *Karl Fischer method*. From the result shown in Fig. 4(b), a fuel replacement interval of 8 days (192 hr) is needed to keep the *TAN* below the deterioration limit. Finally, no change of the water content of the fuel was detected in this period.

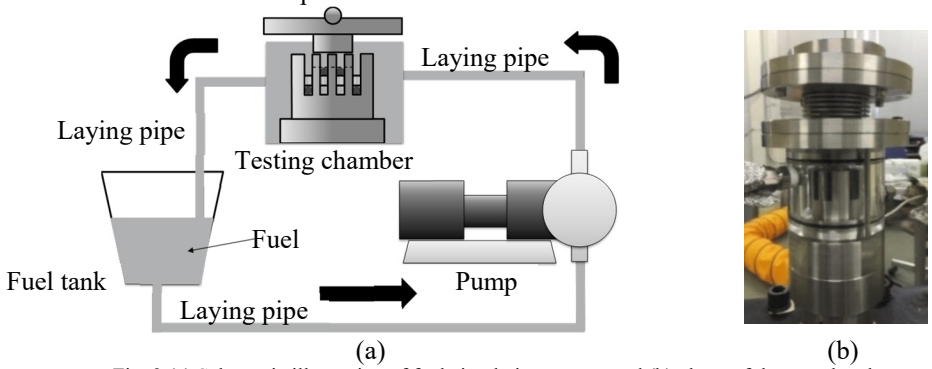

Fig. 3 (a) Schematic illustration of fuel circulation system and (b) photo of the test chamber.

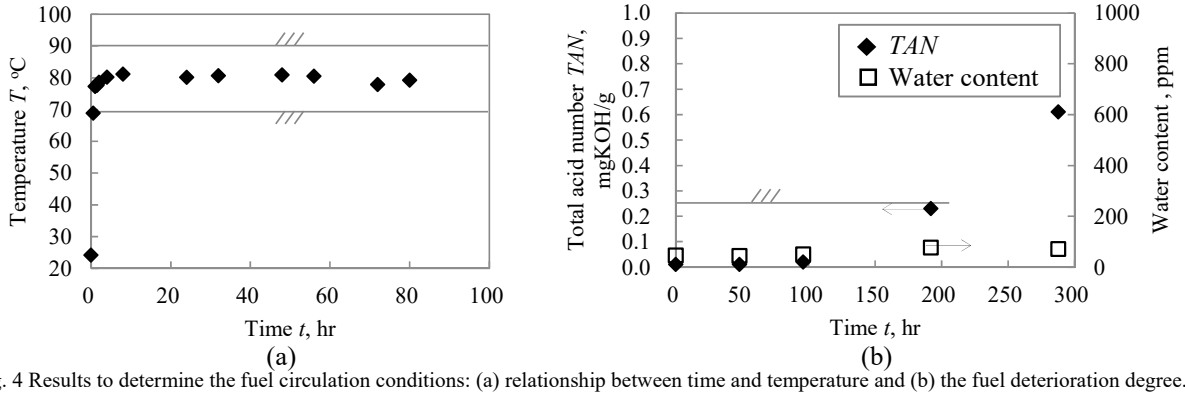

Fig. 4 Results to determine the fuel circulation conditions: (a) relationship between time and temperature and (b) the fuel deterioration degree.

2.3. Fuel

As introduced in the previous section, some fatigue tests were carried out in fuel environment. Under such conditions, the fuel accepted in this study is commercially available diesel oil, which satisfied the *Japanese Industrial Standards* (JIS2). In order to measure the fatigue strength reduction in diesel oil, the other fatigue tests were undertaken in air.

3. Experimental results

3.1. Fatigue results in diesel oil

Before performing a fatigue test in diesel oil, to confirm whether corrosion occurs on the surface of specimen in diesel oil or not, the long-term immersion tests without any mechanical load were conducted. After 192 hr immersion, the corrosion mark was not confirmed on the surface of the specimen, seeing any change of the surface roughness.

As a second step, fatigue tests (*S-N* diagram) in air and in diesel oil were conducted, giving the *S-N* results shown in Fig. 5. Stress range $\Delta\sigma$ (= σ_{max} - σ_{min}) is plotted against the number of cycles to failure in logarithm scale. Fatigue limit was determined by the staircase method. Solid mark of staircase section means broken specimens, and open mark means the unbroken ones at 10^7 cycles. As a result of fatigue test, the slope of fatigue strength in low cycle range is the almost the same in air and in diesel oil, and fatigue strength in diesel oil was improved than in air. On the other hand, both in air and in diesel oil, the slope in high cycle range is different from that in low cycle range, inducing an intersection of *S-N* curves at about $N = 2\times10^5$. Fatigue limit in air was σ_w = 853 MPa and in diesel oil was σ_w = 742 MPa. Thus, the fatigue limit decrease due to diesel oil is about 100 MPa.

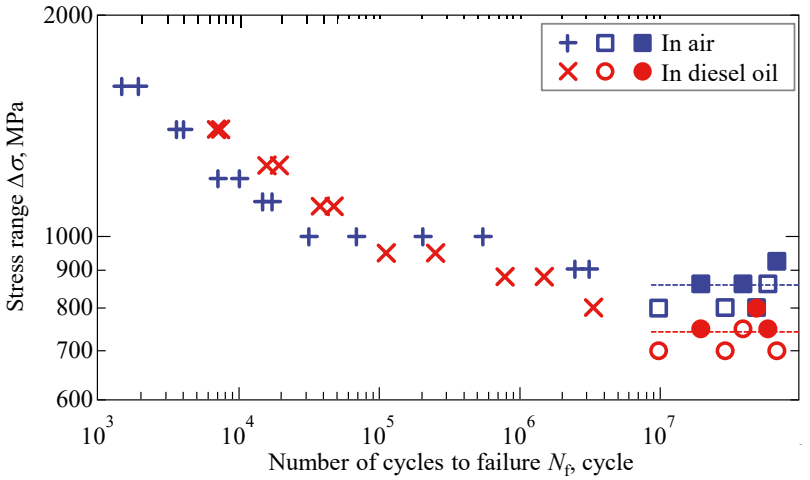

Fig. 5 *S-N* diagram of JIS SCM 415 tested in air and in diesel oil.

3.2. Results of fracture surface observation

The fracture origin was observed with a scanning electron microscope (SEM). The typical features of fracture surface tested in air are shown in Fig. 6 and in diesel oil are shown in Fig. 7, respectively. In all test conditions, fracture origin types were classified into two patterns, one showing is an intergranular fracture with inclusion and the other is that without inclusions near the surface. A careful fractography does not detect any significant influence of test environment on the fracture surface. In addition, vicinity of the fracture origin showed a transgranular fracture and carburized layer near the specimen surface was intergranular fracture. Corrosion mark was not observed on the fracture surface in diesel oil. The elemental analysis of the inclusions at the crack origin was performed with energy dispersive X-ray spectrometry (EDS). The analysis results for cases of tested in air are shown in Fig. 8, whereas for cases of tested in diesel oil are shown in Fig. 9. An aluminium, bismuth and some oxygen were detected at the inclusion site.

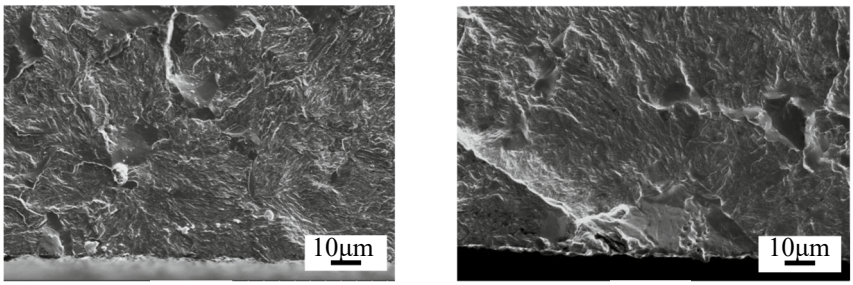

Fig. 6 Typical feature of fracture origin tested in air: (a) intergranular fracture with inclusion, $\Delta\sigma$ = 903 MPa, $N_f = 3.2\times10^6$ and (b) intergranular fracture without inclusion, $\Delta\sigma$ = 950 MPa, $N_f = 1.1\times10^5$.

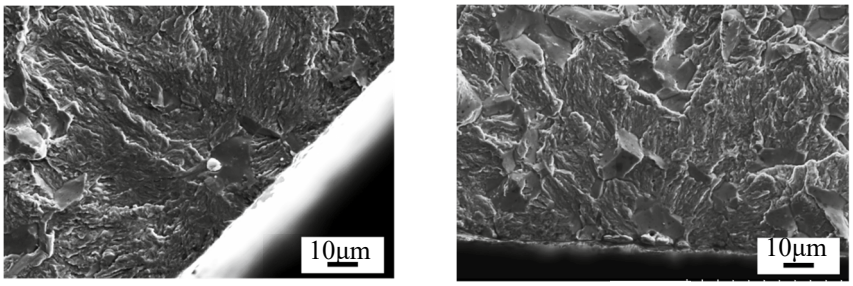

Fig. 7 Typical feature of fracture origin tested in diesel oil: (a) intergranular fracture with inclusion, $\Delta\sigma$ = 863 MPa, $N_f = 5.4\times10^4$ and (b) intergranular fracture without inclusion, $\Delta\sigma$ = 1250 MPa, $N_f = 1.6\times10^4$.

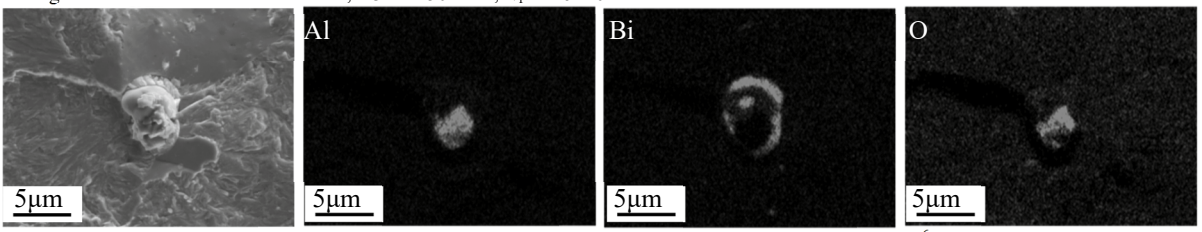

Fig. 8 Element analysis of the inclusion tested in air: $\Delta\sigma$ = 903 MPa, $N_f = 3.2\times10^6$.

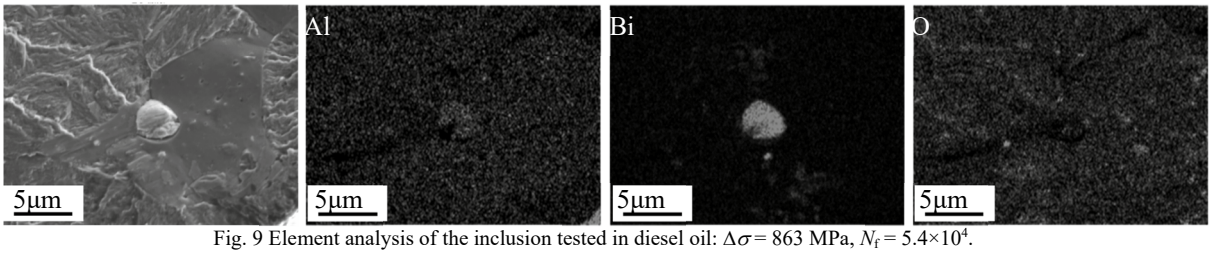

Fig. 9 Element analysis of the inclusion tested in diesel oil: $\Delta\sigma$ = 863 MPa, $N_f = 5.4\times10^4$.

4. Discussion

From the results of SEM and EDS analysis, *S-N* diagram can be classified into two categories concerning fracture origin types, as shown in Fig. 10. In case of $N_f < 3\times10^4$, the fracture is originated from grain boundary near the specimen surface giving a higher fatigue strength in diesel oil than in air. On the other hand, in case of $N_f > 3\times10^4$, the fracture originated from inclusion located at grain boundary resulting in a tendency to have a higher fatigue strength in air than in diesel oil.

The influence of oil environment on fatigue strength has been studied by several researchers and two major explanations were discussed. One is a wedging effect and the other is a shut out air and/or moisture effect. Both effects function as suppressing the fatigue crack propagation rate and also as decreasing in fatigue life. In this study, to investigate the above mentioned effects on fatigue strength, the ratio of fatigue crack initiation life to the total failure life was investigated. As one can deduce from Fig. 11, the fatigue crack initiation life accounted for about 90% of the fatigue life. Such a behavior can be explained by the low toughness usually reported for JIS SCM415 high strength steel. Therefore, fatigue strength change in this study is probably due to the influence of diesel oil on crack initiation.

In order to examine the effect of the diesel oil on the specimen, the elemental analysis on the tensile surface of the specimen which were broken at $N_f > 3\times10^4$ was carried out by electron prove micro analyser (EPMA). The results of the analysis tested in air are shown in Fig. 12 and in diesel oil are shown in Fig. 13, respectively. From the results, O, Si, and C had been concentrated in the specimen in diesel oil compared to in air. The reduction of fatigue strength at $N_f > 3\times10^4$ is considered to be caused by some influence of the diesel oil deterioration which progress with the fatigue test.

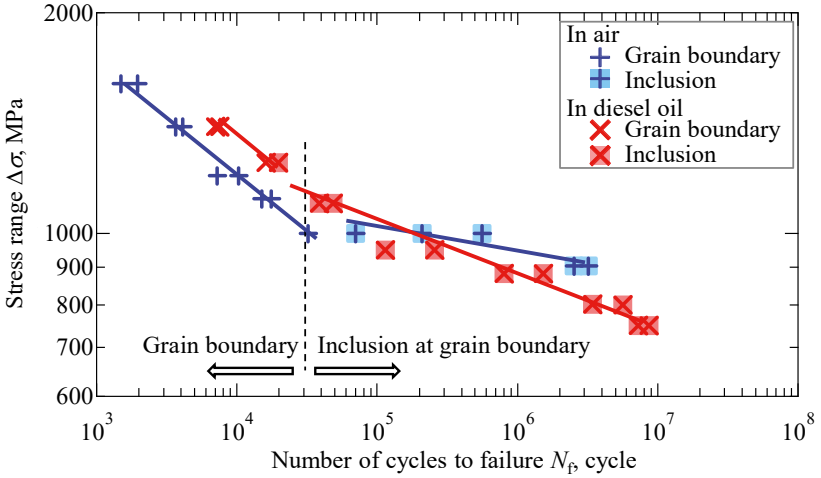

Fig. 10 *S-N* diagram classified into each type of fracture origin.

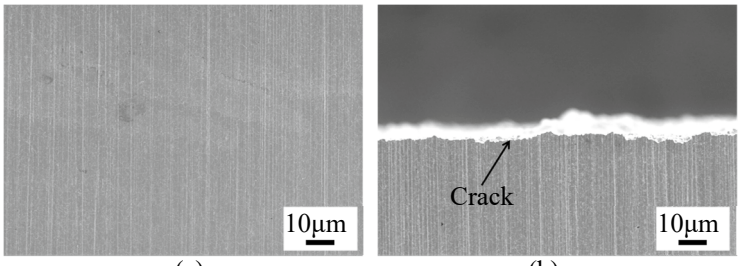

Fig. 11 SEM of specimen surface tested in diesel oil at $\Delta\sigma = 900$ MPa: (a) after $N = 6.0\times10^5$ no crack found and (b) $N_f = 7.4\times10^5$ final failure of specimen.

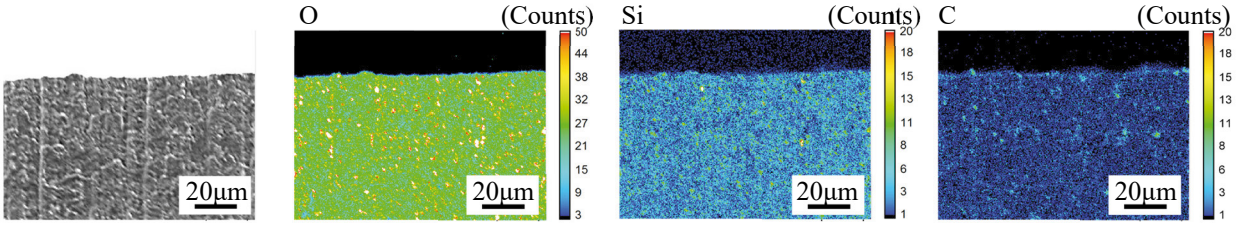

Fig. 12 Elemental analysis of tensile surface tested in air: $\Delta\sigma = 903$ MPa, $N_f = 3.2\times10^6$.

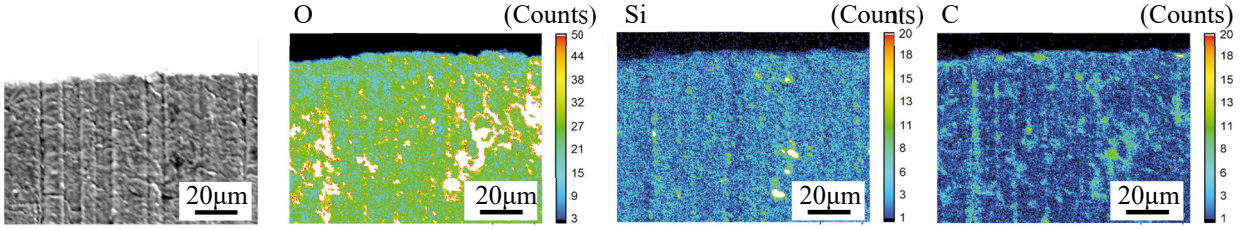

Fig. 13 Elemental analysis of tensile surface tested in diesel oil: $\Delta\sigma = 800$ MPa, $N_f = 3.4\times10^6$.

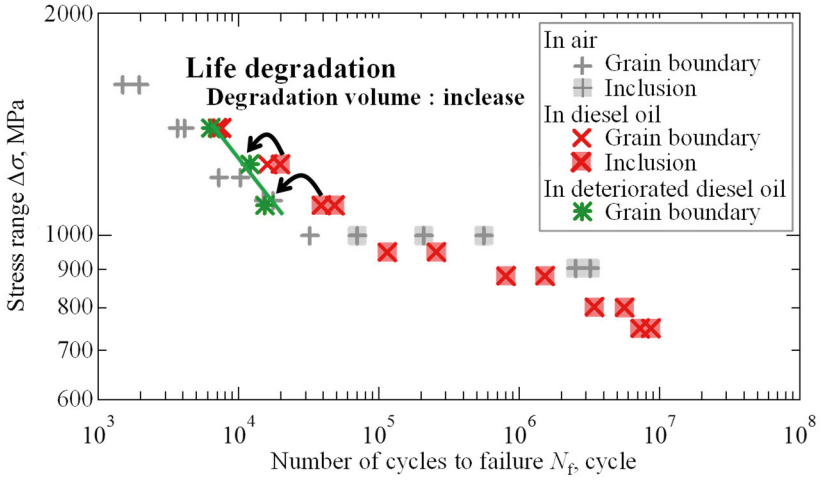

Fig. 14 *S-N* diagram including tests in deteriorated diesel oil.

On the other hand, the fatigue test at $N_f < 3\times10^4$ is usually finished within one day, so diesel oil does not have the time to deteriorate. In order to better assess the effect of deterioration of diesel oil on fatigue properties, a few fatigue tests were conducted in the deteriorated diesel oil at a relatively high stress range, in order to break the specimen at $N_f < 3\times10^4$. *S-N* diagram of related fatigue tests is shown in Fig. 14. As a result, fatigue life tends to shorten compared to the fatigue tests conducted in non-deteriorated diesel oil. Therefore, it was found that the diesel oil deterioration should be considered as one of the important factors to explain the decrease of fatigue strength.

5. Summary and conclusions

A newly experimental method has been developed in order to conduct fatigue test in fuel environment. From this method, fatigue properties in diesel oil of JIS SCM415 were investigated. The obtained features were also compared to results in air and the effect of the diesel oil was studied.

The major conclusions are as follows:

(1) There are no corrosion marks in the specimen in fuel. And, fatigue limit in diesel oil was σ_w = 742 MPa which is lower than in air (σ_w = 853 MPa).
(2) Regardless the fatigue test environment (air or diesel oil), the fracture origin in low cycle range ($N_f < 3\times10^4$) exhibits intergranular fracture without inclusion, and that in high cycle range ($N_f > 3\times10^4$) shows intergranular fracture with inclusion. Inclusions consisted of aluminium, bismuth and some oxygen.
(3) The concentrated parts of O, Si, and C were observed on the tensile surface of the specimen tested in diesel oil.
(4) The diesel oil deterioration is considered as one of the important factors to explain the decrease of fatigue strength.

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